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Problem-Solving by Immersive Virtual Reality: Towards a More Efficient Product Emergence Process in Automotive

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***Abstract*— The Automotive Industry has been actively investigating how Virtual Reality (VR) hardware and software platforms could provide new enhanced design tools since the end of the nineties, when DaimslerChrysler AG produced DBView, one the first software platforms for immersive visualisation and manufacturing simulations used in Automotive, featuring higher interaction with virtual objects through physics simulation. Since then, VR technologies have evolved further. Today interactive 3D immersive environments can be used to provide more efficient ways to solve problems and improve design choices at very early stages of new product developments. This paper analyses how Automotive (and Manufacturing in general) can benefit from the adoption of VR tools when they are examined from a problem-solving perspective in the context of the Product Emergence Process (PEP). Two areas of product development have been considered for this purpose: Quality Assessment and Process Planning. Related demonstration scenarios have been developed at the Virtual Engineering Centre of the University of Liverpool with the purpose of carrying out an exhaustive evaluation of benefits gained by the adoption of VR technologies in new product developments.**

Keywords — Virtual Reality; Immersive Enviroments; Product Emergence Process; Automotive

I. INTRODUCTION

Reducing cost and improving time-to-market without compromising (possibly increasing) product quality have always been primary targets of the Automotive Industry since the times of Henry Ford. And the need of developing and building new car models more and more efficiently has indeed spread related technology innovation to other sector of manufacturing. Over the decades methods and strategies to achieve better products with reduced lead times have gradually been extended from the production phase to the whole product life cycle [1]. The extensive literature on the subject shows how this evolution has been made possible by an increasing capability of dealing with and solving problems at earlier and earlier stages of the development of new products [1] [2] [12] [13] [14].

One of the most important contributing factors to the increase of early problem-solving capability in the Automotive Industry is the evolution of hardware and software platforms able to create and manage virtual models of products and processes. Indeed, Automotive has always played a role of innovation catalyst for modelling and simulation technologies in industry. More and more efficient data management and advanced virtual technologies have drastically shortened problem identification times and problem-solving cycles. However, the amount of dataset and their interconnections grow in extension and complexity as new car models are developed. The advent of self-driving cars is just an example. The Automotive Industry is particularly aware of the challenge posed by the increasing modelling complexity to efficient problem-solving, a challenge that cannot be faced by using only traditional desktop-based CAD and CAE tools. Recent advancements in computer graphics and motion tracking enable humans to manage and use development workstations more interactively and, as a consequence, more efficiently. Nowadays immersive Virtual Reality environments (IVEs) offer a more natural medium to visualize and manipulate data through intuitive, spatial understanding, increased information bandwidth and dynamic, collaborative spaces [3] [4].

This article examines IVEs in a problem-solving perspective, focusing on their use in the Automotive Industry. First, the concept of **Product Emergence Process** (**PEP**) in Automotive is introduced [5] [6] [7]. The PEP is the framework of activities used in modern vehicle engineering to develop new products. Each phase of the PEP is characterized by specific types of developments requiring different and specific tools. It is therefore important to evaluate what is the best tool to use for a specific product development phase, in order to optimize problem-solving efficiency. This aspect is considered in section 3 and proposes a method to evaluate applications problem-solving efficiency, which is an essential parameter to consider when investments in new modelling technologies have to be considered. Section 4 analyses the determining factors that make IVEs more efficient in identifying problems and finding solutions (*issue capture and resolution*).

Finally, we see how VR immersive technology can be effectively applied at different stages of the PEP. Some examples of the use of IVEs for quality assessment and manufacturing process analyses that would straightforwardly reduce time and cost by implementing early problem-solving techniques in PEP are shown. Related demonstration scenarios have been developed at the Virtual Engineering Centre (VEC) of the University of Liverpool. They will pave the way for a more accurate evaluation of benefits gained by the adoption of VR technologies in new product developments.

II. Product Emergence Process (PEP) and Front-Loading Problem-Solving

The Product Emergence Process (or Product Evolution Process according to the initial definition by Julian Weber [5]) is the framework of activities used in modern vehicle engineering to develop new products. According to some authors, it can be broadly divided in 4 main phases: **Target Definition, Fuzzy Front-End, New Product Development** and **Rump-up** [6]. The PEP structure, however, can be further refined by including tasks, gateways and deliverables to coordinate in detail all the activities related to the development of a new product, from conceptual stage to manufacturing and delivery to customers [7]. The PEP framework has been initially implemented in the German Automotive Industry, but the underlying concepts can be broadly applied to other manufacturing sectors. It also offers a platform for a new, interdisciplinary and integrated learning environment for industrial engineering [8].

A constant effort is made to reduce the duration of PEPs, otherwise and more commonly known as time-to-market, for new products. The performance in developing and delivering new products to market is a crucial aspect of modern manufacturing across all areas. There is undoubtedly a competitive advantage in creating products that meet customer needs efficiently and in a timely manner [1]. Reducing time and effort in a PEP can be achieved across all its phases and involving all stakeholders. To cite a few cases, Göpfert and Schulz analyze how integrating Logistics in the PEP for the Automotive Industry can indeed improve overall efficiency not just when is considered in New Product Development, but as early as the Target Definition phase [6] [9]. Other works consider the impact on the PEP by new knowledge management [10] and data mining methods [11] applied at early production planning phases. No matter the specific area considered, most of the effort is clearly aimed at finding methods that shorten development times by solving problems efficiently and as early as possible in the development process of a new vehicle. In the past decade a consolidated research shows how high performances in product development greatly depend on problem-solving capabilities at creation and design phase [1] [2] [12] [13]. This strategy is defined as front-loading problem-solving (FL-PS). According to the definition given in [2],

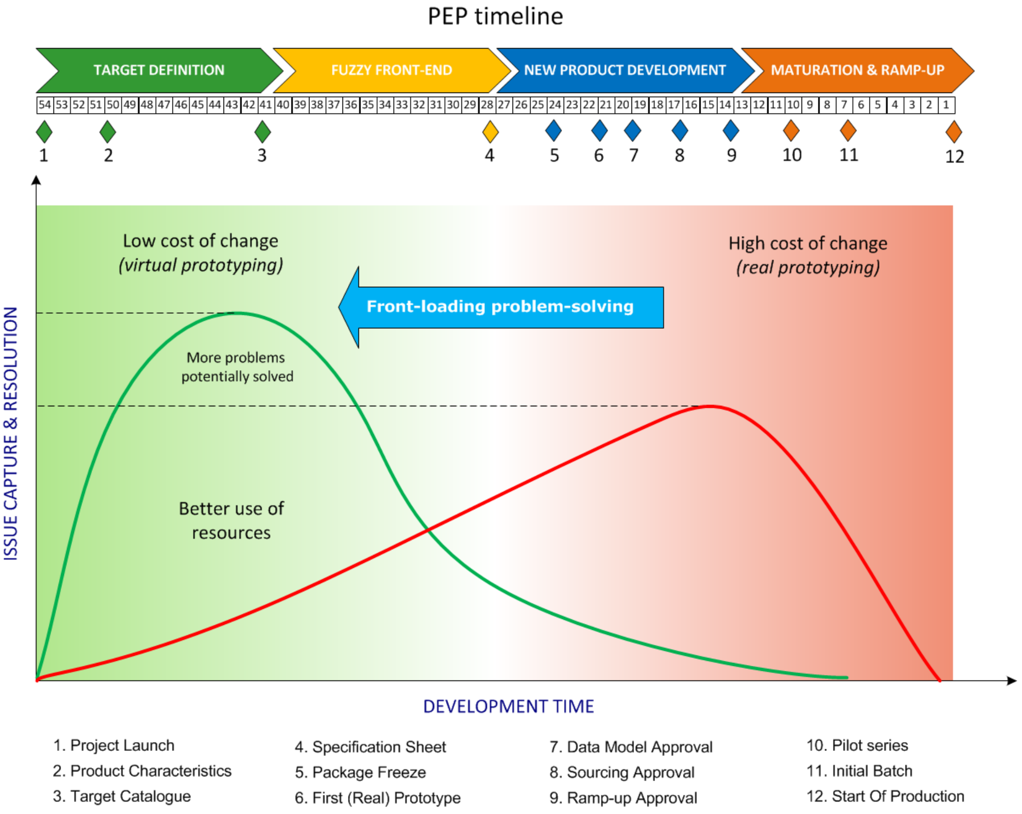

Fig. 1. *Implementing front-loading problem-solving in a product emergence process (PEP) results in lower cost of development changes and higher number of resolved issues*

FL-PS seeks to improve development performance by shifting the identification and solving of (design) problems to earlier phases of a product development process.

The first immediate benefit of FL-PS is reduction of lead-time. In the Automotive Industry this is achieved by following two main approaches, both resulting in reduced number of problem-solving iterations and shorter iteration cycles: *knowledge transfer*, which exploits design solutions and manufacturing processes adopted in previous car models, and *rapid problem-solving* [2]. The latter makes use of advanced virtualization and digitalization methods to create a "virtual product" from the early stages of development, increasing and extending model complexity as product design grows, up to pre-production phases. The effects of FL-PS by virtual prototyping on PEPs can be schematically represented in the chart of Fig. 1. Virtual prototyping performed at early stages of a new product development process, from conceptual level (Target Definition) throughout design and product validation (Fuzzy Front-End and New Product Development) allows to capture more issues and, consequently, solve more problems when changes in product configurations can still be carried out at low cost (green curve in Fig. 1). Also, the possibility of changing and testing more easily different options and "what-if" scenarios on digital models increases the chance of pre-empting potential issues at later stages of development, raising the amount of problem solved when compared with real prototyping methods. The final outcome is reduction of time-to-market, better use of resources (less tasks and process evaluations in the PEP) and better product quality.

In the following of this article we focus on rapid-problem solving and examine how IVEs can crucially contribute to improve PEP performance by shifting problem-solving capabilities at earlier stages of the PEP, at the same time shortening design iteration cycles in phases where more traditional modelling and simulation tools are used. To this purpose a more quantifiable evaluation of how efficient virtual modelling tools are when compared to each other could be useful. This is particularly true when it comes to adopting VR technologies. Moving from traditional modelling and simulation environments to IVEs involves important changes in large companies, in some cases a true "change of culture". It is therefore essential to have a more objective method for quantifying benefits introduced by IVEs and justifying investments and implementation of new assessment procedures among all stakeholders involved in the product development.

III. PROBLEM-SOLVING EFFICIENCY

Nowadays a new car can be virtually "built", reviewed and tested across most of the initial PEP phases, up to a point where it is fully, digitally represented (Digital Mock-Ups - DMUs [14]).

Virtualization on its own, however, does not directly imply problem-solving efficiency. Attention must be paid in selecting the most suitable tool for the job. Fig. 2 expands the diagram shown in [2] to highlight a potential efficiency issue to consider when choosing CAE tools. If modelling times for the creation and management of a virtual prototype are not carefully considered, the risk of extending development times beyond acceptable limits is high. For this factor to be properly taken into account, we assume the time saved in solving problems by using real prototypes and virtual ones (*front-loading time*) depending also on preliminary phases when the prototype (real or virtual) is built and experiments/simulations are prepared:

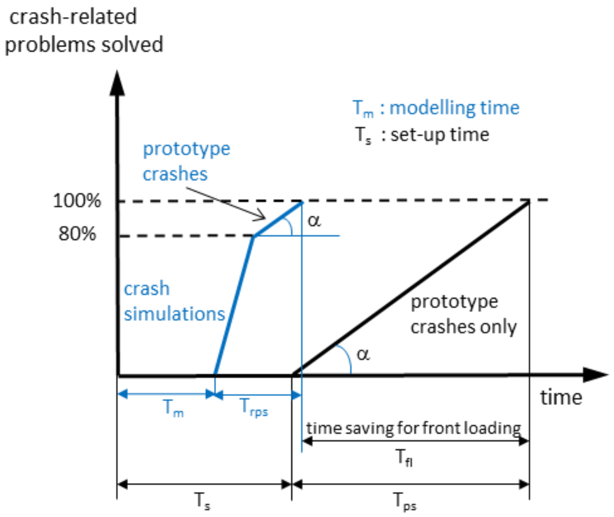

Fig. 2. *Effect of crash simulations on problem-solving showing time saving for front loading (rapid problem-solving)*

$$T_{fl} = (T_{ps} + T_s) - (T_{rps} + T_m) = (T_{ps} - T_{rps}) + (T_s - T_m) \qquad (1)$$

where:

T_{fl} : time saving for front-loading;
T_{ps}: time used to complete all problem-solving cycles for real prototypes;
T_s: set-up time for experiments with real prototypes (includes prototype building);
T_{rps}: time used to complete rapid problem-solving cycles (with virtual models);
T_m: modelling time (of product and related processes to simulate);

In this formula we separate times strictly required for problem-solving iterations from the preparatory (modelling and/or experiment/simulation set-up) phase. The same equation can be used to compare different virtual platforms. For example, some tools might have longer modelling times but shorter problem-solving cycles and, most of all, the possibility of addressing and solving more problems at the same time. The benefit of parallel problem-solving on product development performance has been already examined in literature [12] [13].

An effective deployment of IVEs in industry must be evaluated with (1) in mind. In some cases preparation times to model product and processes in IVEs might take longer than traditional desktop-based CAE applications. However IVEs can be successfully used when they provide unique and/or very efficient problem-solving capabilities. To mention one of the most recurrent cases, the possibility for a real person to be involved in a virtual assembly scenario allows for the evaluation of several issues (ergonomics, process feasibility, cycle times, etc.) at the same time, in parallel. This could be hardly done by using a mannequin in a desktop-based simulation scenario, unless sophisticated animation techniques are used.

The examples described in section 5 shows more in detail how current VR technologies, through advanced visualisation and virtual environment interaction, can provide more effective problem-solving platforms in two crucial areas of product development: Quality Assessment and Process Planning.

IV. VR AS A PROBLEM-SOLVING PLATFORM

Modelling and simulation tools are extensively used in Automotive to increase FL-PS in PEPs. Indeed, Automotive Industry is becoming the manufacturing sector taking most advantages out of virtual technologies. In the same way as product development in Automotive has been influential in the development of Digital Manufacturing software, the latest engineering applications exploiting VR technology are mainly driven by Automotive requirements. But how IVEs can provide more efficient FL-PS than already existing CAE tools? Is it possible to push problem-solving at earlier stages of PEP (and reduce development time even further) by using IVEs?

To answer these questions, we shall consider three characterising factors of IVEs that can help in evaluating this technology from a problem-solving perspective: **presence**, **immersion** and **interaction** [3] [15].

Presence is defined as “the subjective experience of being in one place or environment, even when one is physically situated in another” [15]. Presence is the individual response of a subject immersed in an IVE and differs from subject to subject. Immersion and interaction affect presence. Psychology tests used to evaluate presence can be indirectly used to determine the effectiveness of immersion and/or interaction in an IVE. However, although presence is generally an important factor in IVE design and plays an important role in areas like Psychology, Medicine and Education/Training, to a first approximation is not as crucial as immersion and interaction for manufacturing planning.

Virtual environment immersion, when compared to conventional desktop-based applications, offers better perception and 1:1 scaled model representation, therefore providing an enhanced and intuitive, spatial understanding of data. Also relationships among datasets are easier to observe and process.

The level of visual immersion is quantifiable and linked to the following visual variables [3]:

- Field of view (FOV)
- Field of regard (FOR)
- Display size
- Display resolution
- Stereoscopy
- Head-based rendering (change of image perspective by head tracking)
- Realism of lighting
- Frame rate
- Refresh rate

Whereas immersion allows “seeing” things in a more realistic fashion, interaction provides intuitive means to “do” things in an IVE. Human-centred simulation in IVEs (i.e. when the operator immersed in the environment is actively involved in the simulation) can only be performed with some degree of interaction. Interaction usually involves a physics engine embedded in the VR software through which is possible to detect collisions between virtual objects. Some of the virtual objects are virtual counterparts of interactive (real) devices, or even virtual hands and representations of the full operator’s body (avatars/mannequins). The coupling of virtual object-real interactive device is realised by detecting device movements in the real world through a tracking system. Acquired position data are sent to the immersive software to drive virtual counterparts. For mannequin tracking the operator usually wears a tracking suit to detect body postures, although other low-cost technologies based on motion tracking devices for video games (Kinect) have been explored [16].

Interaction is also quantifiable and depends on how many devices/modes are used by the subject to acquire information and modify the environment (Multi-modal environments [17]). Typical interactive devices are 3D mice, data gloves, Wii-motes and force-feedback/haptic arms/joysticks. Based on the vast amount of examples in literatures (the most significant of which reported in [3]) we can state that, without loss of generalisation, *the problem-solving capability of IVEs improves when immersion and interaction are implemented in the environment to a certain extent*. However, above a threshold that is greatly dependent on the specific application/model/simulation, higher levels of immersion and interaction do not necessarily involve more efficient IVEs from a problem-solving point of view [3] [17] [18]. The right “amount” of immersion and interaction should be carefully considered case by case to avoid too complex IVEs, with possible consequent drawbacks on equipment cost, data handling efficiency and longer modelling/set-up times (T_m in (1)).

V. VIRTUAL ENVIRONMENTS AND PEP IMPROVEMENTS

The right balance between immersion and interaction in IVEs for Automotive design and development is one of the areas of investigation at the VEC – University of Liverpool. We aim at enhancing the performance of product development in the Automotive Industry through the exploitation of immersive virtual technology for high fidelity analysis and virtual prototyping. One of the objectives of the VEC is to improve performance in two large areas of activities usually carried out in PEPs: Quality Assessment and Process Planning. Both areas cover several stages of the PEP, quite crucial for the cost and time savings potentially attainable.

A. *Virtual Quality Assessment*

An important factor affecting the development of a new car in the Target Definition and Fuzzy-Front End phases of the PEP is the so-called perceived quality of split-lines [19]. Perception of split-line quality from interior and exterior aesthetics of a car is a key factor for conveying the image of a superior product and is fundamental for high-end automotive products. Each PEP review stage during the concept and initial design of a new car are driven mostly by perceived quality assessments. The traditional way to carry out assessments on interior and exterior aesthetics is by assembling modifiable prototypes of new cars and run evaluations on real components, which is, obviously, a very time-consuming and expensive activity. Also, real prototypes can only be built at advanced stages of design, deeply affecting the possibility of front-loading potential problems. By combining immersion with high fidelity data representation, IVEs can provide a much less costly and more rapid problem-solving platform for perceived quality assessments. CAD data of a new car can be directly projected in stereoscopic 3D on large screens (powerwalls) in a 1:1 scale (Fig.3). Then, parts affecting the perceived quality can be modified in position, size, etc. (geometrical variations) according to a predefined number of choices already considered at design stage.

For example, a typical problem in the design of new car interiors is the door-to-dashboard gap (Fig. 4). The best door position (in terms of height and distance from the dashboard), or, rather, the position where it "looks right", greatly depends on the point of view of the driver. Reviewers can "sit in the virtual car" on a seat mock-up that reproduces the exact configuration as the real car seat. Reviewer's head and seat mock-up are tracked in the visualization room in order for the image projected on the screen to be aligned with the seat and adjusted based on observer point of view (Fig.3). Initial Virtual Quality Assessments can be carried out as soon as the concept design of a new car is in advanced state of definition, which normally happens before the end of the Target Definition phase in the PEP. Considering the time when the first real prototype of a new car is usually built (almost half-way through the New Product Development phase – Fig. 1), this means a front-loading shift of issue capture in Quality Assessment of about 5-6 months.

Fig. 3. *A car interior projected in full scale on a powerwall in 3D stereo. The mock-up of the car seat provides correct posture and point of view to run an accurate perceived quality assessment and detect potential aesthetical issues.*

B. *Virtual Process Planning*

Initial assembly analyses and process planning usually start towards the end of the Target Definition phase in the PEP (milestone 3 in Fig. 1). Improving the evaluation of manufacturing processes at this early stage can highlight potential issues before the design of a new product is finalised, avoiding longer design iterations or expensive remedies towards the end of the product development. Virtual assembly has been indeed one of the first scenarios to be tested as

Fig. 4. *Door-to-dashboard split-line in Bentley Mulsanne*

application of VR in industry [17] [21] [22]. Differently from desktop-based tools for assembly simulation where mannequins are used to evaluate assembly procedures and related ergonomic factors, IVEs can provide a much more direct (immersive) experience to operators involved in a manufacturing process. Interaction and physics-based simulation in IVEs are fundamental to provide, as much as possible, a realistic scenario in which the subject can test actions and acquire information helpful to solve any issue related to the process.

In a typical manually-operated assembly process there are three types of analysis carried out at process planning stage: **part load analysis**, **tool access analysis** and **ergonomic assessment**.

With conventional desktop-based applications these analyses are carried out separately: part load analysis is performed first, followed by tool access evaluations and, finally, ergonomic assessment. In an IVE they can be merged into one assessment task. A typical assembly simulation which makes use of real tracked objects would evolve in this way:

1) the operator grabs the virtual part to be assembled with an interactive media (a real mock-up or replica of the object, or by a Wii-mote or a cyber-glove) and evaluates how to fit the part (part load analysis);

2) the part is set in place; the operator grabs the real tool which has a virtual counterpart in the assembly scenario; he/she operates the tool to perform the required assembly action (tool access analysis);

3) if the operator wears a tracking suit, body postures can be tracked and recorded for the whole duration of the simulation, providing data for the ergonomic analysis.

At simulation time, collisions between part and surrounding objects and between tool and surrounding objects are highlighted by a number of sensorial cues, like colour change (visual cue), vibration on the device held/worn by the operator (tactile cue) and sound (audible cue), in order to alert the subject when a corrective action must be taken or the action is correct. It is also possible to use force-feedback devices that

Fig. 5. *Simulation of a front-seat assembly using the OPTIS HIM software platform*

provide a reaction and a more natural feeling in case of object collision, but this option is still too expensive to be largely adopted and in most cases constrains operator movements.

An immediate advantage with respect to desktop-based simulations is the more accurate ergonomic assessment carried out in IVEs. Body postures must be timed for correct health and safety evaluations. A posture, which is uncomfortable but still in acceptable limits, might become risky if it is kept for too long. Simulations carried out in IVEs can provide a full, detailed record of all movements, instead of static postures usually evaluated in digital manufacturing software.

The second contributing factor to more efficient problem-solving is the combination of different problems normally solved in sequence into one task. Besides time saving, combining the three analyses in one scenario could highlight issues not detectable when tests are run separately. Part load analysis, for example, is based on the evaluation of object trajectories that do not take into account ergonomic factors. Also, the involvement of a real person makes the evaluation of different options and what-if scenarios more quick and flexible than non-immersive simulation platforms, reducing times for alternative trajectory feasibility analyses of part load and tool access.

In Fig. 5 is shown an example of a process simulation in immersive environment. The operator wears an Oculus Rift as immersive visualisation device (head-mounted display) to perform a front-seat assembly. A Wii-mote is used as interactive device to grab and handle the seat. Body postures can be recorded from the mannequin driven by the operator through the tracking system detecting limb position from predefined set of markers. The seat is supported by a lift assistor and is therefore constrained in its movements. In this way the operator can evaluate the exact sequence of actions to perform in order to put the seat in place without causing damages to interior or exterior parts of the car. The powerwall is used in this case as advanced visualisation medium for other potential team members, to visualise the field of view of the operator (Oculus view) and/or the overall virtual scenario in 3D.

VI. SUMMARY AND FUTURE WORKS

Virtual prototyping of product and processes by immersive VR is gradually becoming an effective and affordable option for manufacturing. In this paper we have examined the potential impact of this technology if adopted in the process of developing new car models in the Automotive Industry. When compared to traditional desktop-based modelling and simulation tools, immersive virtual environments offer unquestionable advantages in terms of front-loading and rapid problem-solving in crucial areas of development. For this purpose, two aspects of product development have been considered for a preliminary evaluation of problem-solving performance: Quality Assessment and Process Planning. The former can greatly benefit from a full-scale representation of a DMU in immersive VR, front-loading any potential issue as earlier as 5-6 months in the PEP timeline. As far as Process Planning is concerned, given the complexity and the number of tasks involved, it is more difficult, at the moment, to quantify the amount of time and resources saved by exploiting immersive VR, although the advantages provided by the possibility of performing multiple analyses at the same time and better ergonomic assessment are evident. Further research is required to find the optimum balance of immersion and interaction in IVEs for Virtual Manufacturing, as well as to evaluate time and cost saving in comparison with desktop-based modelling and simulation tools.

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